A Low Cost Luminescent Solar Concentrator

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Abstract

Two commercially available, ultra-low cost plastics, doped with fluorescent dyes, are presented as novel materials to be used to in luminescent solar concentrator systems. Investigation of the optical properties of the plastics reveals favourable performance characteristics including significant Stoke's shifts and negligible spectral overlap of the emission and absorption spectra. These attributes are supported by experimentally determined optical efficiencies of 9.8% and 16.8%. Limited absorption/emission spectral overlap indicates that self-absorption is a low loss mechanism in these devices. This is confirmed by a weak red shift as the photon path length in the LSC is increased. Finally, the potential for this type of LSC is considered in the context of indoor photovoltaics and solid state lighting.

Introduction

A luminescent solar concentrator (LSC) for photovoltaic (PV) applications should absorb high energy incident photons, down-shift the energy of these photons with negligible self-absorption and concentrate the light to the edges of the LSC via total internal reflection. A major advantage of LSCs is the potential for low-cost concentration since they accept both direct and diffuse radiation, negating the requirement for a relatively expensive tracking system [1].

A further advantage of LSCs is the potential to spectrally match the energy of the down-shifted photons with the energy band gap of edge-mounted PV cells thus minimising thermalisation losses. To that end, the choice of luminescent absorbers embedded in the host LSC matrix is an important one. Historically, organic dyes such as rhodamine B have been used as a result of their high quantum efficiency, low cost and wide range of (spectral) operation [2]. More recently, CdSe/ZnS and PbS quantum dot systems have been investigated as the absorbing species stemming from increased stability, broadband absorbance and size-tuneable emission characteristics [3,4].

Irrespective of the absorbing species, a key requirement is to limit self-absorption inside the LSC. This phenomenon arises as a result of spectral overlap between the absorption and emission characteristics. Therefore an absorbed photon can be emitted and subsequently re-absorbed rather than concentrated to the edges of the LSC. The amount of Stoke's shift between the absorption and emission spectra is typically used to quantify self-absorption losses.

In this work we present the results of measurements on two very low cost, commercially available fluorescent plastics for LSC applications.

Experimental details

Red and blue acrylic plastic sheets of dimensions 100×100×3 mm were obtained from UK plastic supplier. The retail cost of an A5 sample of the red plastic was < £2. Unfortunately, few details about these samples were available from the manufacturer however they are understood to be doped with an organic dye. Measurements of the refractive index for both plastics indicate $n \cong 1.38$ which corresponds to a critical angle of $\theta_c \sim 46.6°$.

Absorption measurements were performed using a Shimadzu Solidspec 3700 spectrophotometer. Fluorescence spectroscopy was performed using a Horiba iHR320 grating monochromoator and Si over InGaAs thermoelectric cooled detector. For these measurements, the plastics were excited using a custom white and UV LED light source. Determination of optical efficiencies was done using a Vishay BPW34 photodiode (~ 7.5 mm^2 active area) operating in photovoltaic mode with an amplifier circuit. Investigation of losses due to self-absorption was performed using a focused 532 nm diode pumped solid state laser.

Results and Discussion

Figures 1[1] (a) and (b) show the absorption and emission spectra for the blue

[1] Correction: the second region of emission (~820-1100 nm) from the blue plastic (figure 1a) has since been determined to be an experimental artefact.

and red plastics respectively. Also shown in figure 1 is an approximate AM1.5 spectrum for reference. Figure 1(a) indicates that the blue LSC has an absorption band in the near UV with a full width at half maximum (FWHM) of ~ 90 nm. Emission for this LSC is characterised by two major regions centred on 466 nm and 929 nm. The Stoke's shift to the first of these is 90 nm while to the second it is 553 nm. The FWHMs of the first and second emission regions are ~ 70 nm and ~118 nm respectively. In both cases spectral overlap with the absorption band is extremely small suggesting that self-absorption is a relatively weak loss mechanism in this LSC. Figure 1(b) shows the corresponding data for the red plastic LSC. Similarly for this device, the spectral overlap between emission and absorption is very small suggesting good potential performance. The Stoke's shift in this case is 141 nm while the absorption and emission bands FWHMs are ~ 125 nm and ~ 76 nm respectively.

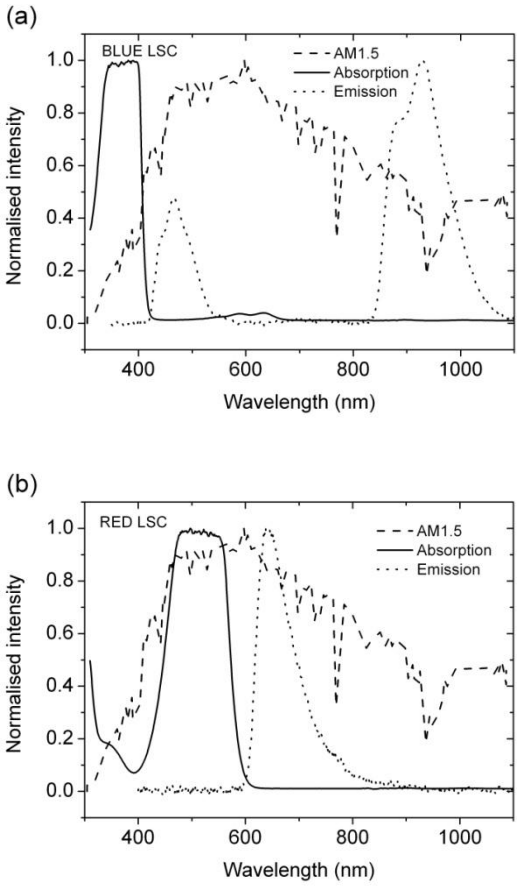

Figure 1: Absorption and emission spectra for the (a) blue and (b) red plastic LSCs. An approximate AM1.5 spectrum is also shown in both cases.

A striking aspect of figure 1 is that with almost no optimisation, these plastics exhibit desirable properties for LSC operation. A feature of the blue LSC is strong down-shifting of photons which is compatible for example with several thin film PV technologies.

Stoke's shift alone is not necessarily a good measure of LSC performance because significant spectral overlap between emission and absorption can still occur. In our samples however, we observe both significant Stoke's shift and negligible spectral overlap which is in contrast to several reports of LSCs based on both organic dyes and quantum dots [3-6]. It is also apparent from figure 1 that a combination of the luminescent species in the two plastics would result in an LSC that absorbs high energy photons across a wide range and down shifts these to wavelengths that are more suitable for conventional photovoltaic technologies.

The optical efficiency η_{opt} of a LSC can be defined as:

$$\eta_{opt} = \frac{I'_{sc} A_{top}}{I_{sc} A_{edge}}, \qquad (1)$$

where I'_{sc} is the short circuit current of a edge-coupled solar cell and I_{sc} is the short circuit current of the same cell under direct illumination. A_{edge} and A_{top} are the area of the edge and top of the LSC respectively. The ratio A_{top}/A_{edge} is defined as the geometric gain and has been shown to be ~10 for optimum η_{opt} [7]. For our samples, the geometric gain is 33.

Measurements of LSC optical efficiency were performed outdoors in diffuse sunlight conditions. For these measurements, three edges of the LSC and the bottom surface were covered in black tape to simulate photon collection and limit reflections back into the LSC. A silicon photodiode was coupled to the remaining edge for measurements of I'_{sc}. Using this technique and equation (1), the optical efficiency of the blue and red LSC were determined to be 9.8% and 16.8% respectively. These values compare well with previously reported figures [8] and are significantly better than quantum dot based LSCs [6].

The relatively high values of η_{opt} for the red and blue LSC are consistent with the absorption/emission measurements in figure 1. To investigate the role of self-absorption further, spatially resolved measurements of the

photoluminescence from the red LSC were performed. For these measurements a focused laser spot was used to excite the sample at a series of points along the top surface sample. A lateral translation stage was used for this purpose such that the points of excitation lay on a horizontal line stretching from the edge of the LSC to the centre. As the laser spot moves nearer to the centre of the sample, the path length that a photon must travel to the detector increases. In turn, this means that there is an increased probability that an emitted photon will be reabsorbed. Re-emission of this photon results in a net red shift in the luminescence spectrum. Figure 2 shows the luminescence from the red LSC as the distance between the point of excitation and the detector was increased by 200 mm. The amount of red shift in the data is small (~ 4 nm), confirming that self-absorption is a relatively weak loss mechanism in this sample. Similar results are anticipated for the blue LSC however, the amount of red shift may be even less as a result of the large Stoke's shift to the second emission peak. For polymers, a large Stoke's shift is expected since they experience a structural change during optical excitation. In contrast however, quantum dots do not experience any structural change and consequently have smaller reported Stoke's shifts.

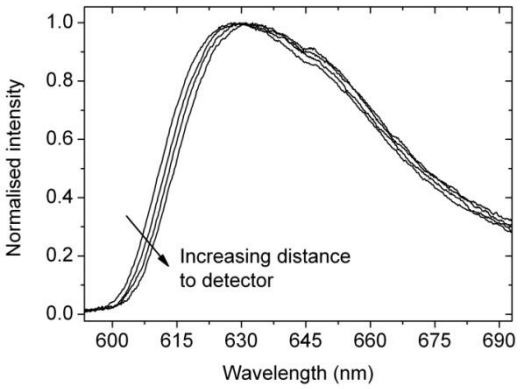

Figure 2: Photoluminescence from red LSC. The different curves were taken as the photon path length from the point of excitation to the detector was increased.

A major issue for organic LSCs is photodegradation [8] and we have not yet investigated this aspect of our LSCs. In the context of indoor photovoltaics however, there is a potential opportunity for our LSCs. Figure 3 shows the red LSC absorption/emission characteristic with the electroluminescence from a white LED shown for reference. It is evident from figure 3 that the absorption spectrum of the LSC is reasonably well matched to the spectrum of the white LED. Furthermore, photons emitted from the LSC are well-suited to Si-based PV devices. In particular, there is a good match between the LSC emission and the energy band gap (also shown in figure 3) of amorphous silicon (a-Si).

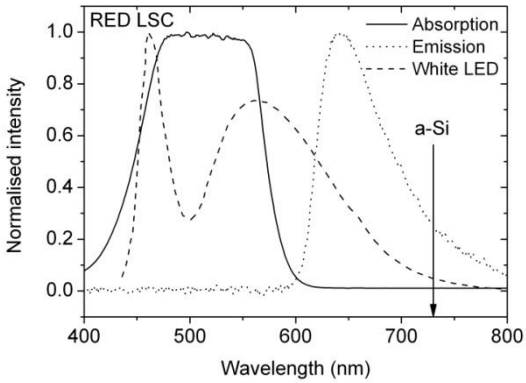

Figure 3: Absorption/emission data for the red LSC shown with electroluminescence from a white LED for reference.

The success of a-Si for indoor PV applications stems from its larger band gap (~1.7 eV), performance under diffuse conditions and low cost. In addition to the spectral match, these attributes fit naturally with the LSCs we have studied. Another factor is the increasing prevalence of solid state lighting (see for example [9]). If indeed, this technology is set to dominate the domestic lighting market then low cost LSCs/a-Si systems could potentially be successful.

Conclusions

We have presented the results of measurements performed on two readily available LSCs. These systems are commercially available acrylic plastics doped with fluorescent dyes. Although LSCs have been studied for a relatively long period, issues with stability and self-absorption remain. With almost no optimisation, our LSCs exhibit good performance characteristics in terms of Stoke's shift, self-absorption losses and optical efficiency. This compares well with previously reported dye based systems and even better compared with quantum dot systems. We suggest that further research is required to improve the stability of dye-based systems and

that an opportunity for indoor PV-LSC systems may exist particularly with increasing deployment of LED lighting.

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